Phase Matching in presence of feedback:
Higher order terms and enhancement of nonlinear interactions.

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Our study shows that higher terms in phase matching conditions, usually neglected, can in fact drastically affect the dynamics in distributed feedback gratings. We showed that phase matching conditions and standard Bloch theory are totally inadequate to predict optimum second harmonic generation when fields overlap and localization effects rule the nonlinear dynamics. We designed an optimized structure based on GaN/AlN stacks for second harmonic generation in the visible range. We also designed an optimised structure based on AlGaAs/AlAs stacks for second harmonic generation in the near infrared range. Our numerical predictions show that the efficiency/size performances have been improved by one order of magnitude with respect to phased matched interactions in similar structures.

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Abstract

Our study shows that higher terms in phase matching conditions, usually neglected, can in fact drastically affect the dynamics in distributed feedback gratings. We showed that phase matching conditions and standard Bloch theory are totally inadequate to predict optimum second harmonic generation when fields' overlap and localization effects rule the nonlinear dynamics. We designed an optimized structure based on GaN/AlN stacks for second harmonic generation in the visible range. We also designed an optimised structure based on AlGaAs/AlAs stacks for second harmonic generation in the near infrared range. Our numerical predictions show that the efficiency/size performances have been improved by one order of magnitude with respect to phased matched interactions in similar structures.

Keywords: Non-linear frequency conversion, photonic crystals, multiplayer stacks.

It has recently been shown that in the presence of feedback there are terms in the nonlinear polarization that do not fulfill momentum conservation [1]. Those terms are generally neglected when one considers cavity enhanced frequency conversion because their contribution averages to zero on a length scale of the order of half a wavelength. Nevertheless, new fabrication techniques make it possible to design, grow, and investigate structures that posses precise and particular nonlinear dipole distributions so that the total field radiated fulfils a new type of phase matching condition even in the presence of dispersive, isotropic media, thus making it possible to take full advantage of field localization. We observed that under these circumstances, the nonlinear regions can be made to emit coherently with huge enhancement factors compared to ordinarily phase-matched bulk materials due to the relevance of higher orders terms. We focused our attention to periodic multilayer structures obtained alternating a nonlinear material with high refractive index and a linear material with low refractive index. Our calculations show that it is possible to maximize the value of the overlap integral between fundamental and second harmonic fields thus optimizing the conversion efficiency [2]. We provided a link between the value of the overlap integral and the phase matching conditions as defined in ref.[3]. We noticed that higher terms in phase matching can not be neglected if the optical thickness of the nonlinear layer is chosen to be less than half-wave with respect to the SH field (roughly a quarter-wavelength with respect to the pump field). Their contribution can in fact be stronger than the effective phase matching conditions defined in ref[3] if the spacing between nonlinear layers is properly designed so that both fields are tuned at band edge frequencies. The result is a further enhancement of one order of magnitude in the conversion efficiency with respect to the one achievable by only effective phase matching considerations. We also investigated the angular emission of second harmonic generation in 1D photonic crystals starting with the Bloch diagrams for the infinite structure. We found that, unlike common bulk materials, phase matching conditions can be fulfilled over a wide angular range. Nevertheless we showed that phase matching condition fulfillment is not sufficient to achieve enhancement of the conversion efficiency. For illustration purposes we calculated the Bloch diagram for an infinite periodic structure with a mixed half-wave/quarter wave unit cell designed following our optimization criteria. We consider a pump wavelength of 1690 nm tuned close to the band edge. Results are shown in figure 1: there is a slight phase mismatch at normal incidence, as predicted by our effective index model. The interaction remains slightly mismatched over a wide angular spectrum and we note that phase matching is achieved for an external incident angle of +- 58.35 degree. Standard theory would predict optimum second harmonic generation for this angle, nevertheless, this model does not allow any prediction on the conversion efficiency for the finite structure. We then calculated the enhancement factor for the finite 20 period structure as a function of the incident angle for the same pump wavelength. As expected by our previous calculations the maximum efficiency is achieved for normal incidence in spite of the phase mismatch.. The angular full width at half maximum (FWHM) of the generated SH field is approx. 5 degrees. Moreover we note that the conversion efficiency is almost equal to zero for the phase matched interaction (fundamental angle at 53.35 degrees. Standard Bloch theory is totally inadequate to predict optimum second harmonic generation when fields' overlap and localization effects rule the nonlinear dynamics.

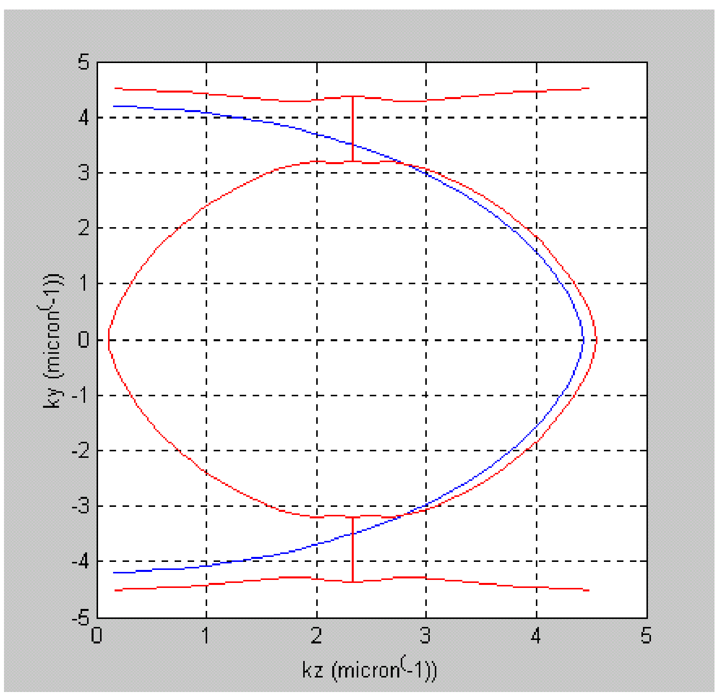

Figure1: equifrequency curve for the fundamental field (blue) and for the second harmonic (red). We remind the reader that for the SH field we rescaled the wavevector components by a facto of 2 to put in evidence phase matching conditions which are obtained at the crossing points between the two curves.

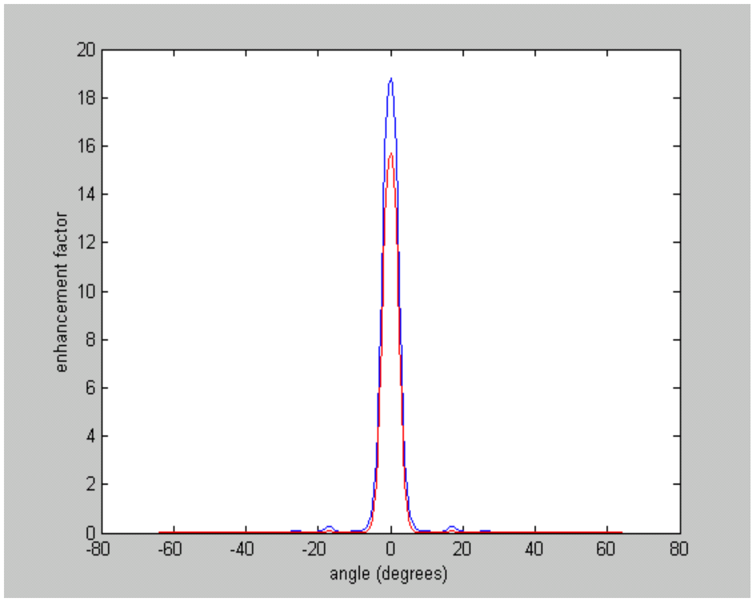

Figure2: enhancement factor as a function of the pump incident angle for forward SH generation (blue) and backward SH generation (red).

Then, we focused our attention on the design and optimization of mulitlayered structures working as high efficiency frequency second harmonic generators taking advantage of field's overlap. We theoretically analyzed the optical properties of Al(0.3)GaAs/AlAs stacks for near IR applications and GaN/AlN for the visible range. In particular we found the right parameters so that the conversion efficiency is optimized when both fundamental and second harmonic fields are tuned at the band edge resonance increasing the performance vs. size efficiency ratio by over an order of magnitude with respect to the best predictions based on photonic crystal technologies. We designed an optimized structure based on GaN/AlN stacks for second harmonic generation in the visible range. The structure is symmetric and composed by 21 periods plus a GaN layer on a Al_2O_3 substrate. The thickness of the layers has been chosen so that d(GaN)=95.9 nm and d(AlN)=140.27 nm. This setup allows tuning of the pump field at the band edge resonance for a wavelength approximatively of 1075 nm.. According to our theoretical model, and considering the natural refractive index dispersion of GaN and ALN, the second harmonic field is tuned at higher order band edge resonance. The structure has been designed taking into account the effects of higher terms in phase matching, thus, the nonlinear layer thickness (GaN) is less than quarter wavelength for the fundamental field. In this condition, the overlap integral is maximized and we predict the maximum enhancement factor for both forward and backward generated fields. Our numerical predictions show that the efficiency/size performances have been improved by one order of magnitude with respect to our previous designs. Finally, we designed a structure based on Al(0.3)GaAs/AlAs stacks for second harmonic generation in the near IR range. The structure is symmetric and composed by 37 periods plus a Al(0.3)GaAs layer on a GaAs substrate. The thickness of the layers has been chosen so that d(AlGaAs)=160 nm and d(AlAs)=90 nm. This setup allows tuning of the pump field at the band edge resonance for a wavelength approximatively of 1584 nm for an incidence angle of 37 degrees. In this case the second harmonic is tuned at the first resonance after the second order band gap. We note that the nonlinear interaction is strongly mismatched for these tuning conditions and, due to the high amount of index dispersion of AlGaAs and AlAs, it is not possible to obtain effective phase matching at these wavelength range. Nevertheless the overlap integral is maximized and the overall conversion efficiency is one order of magnitude bigger than in the phase matched case. In figure 3 we show the results of the calculation of the normalized second harmonic generation efficiency versus the filling ratio of the AlGaAs layer with respect to the unit cell size. We found that that the maximum efficiency for these tuning settings is found when the filling ratio is equal to 0.64. Then we designed a 45.5 period and a 55.5 period structure.

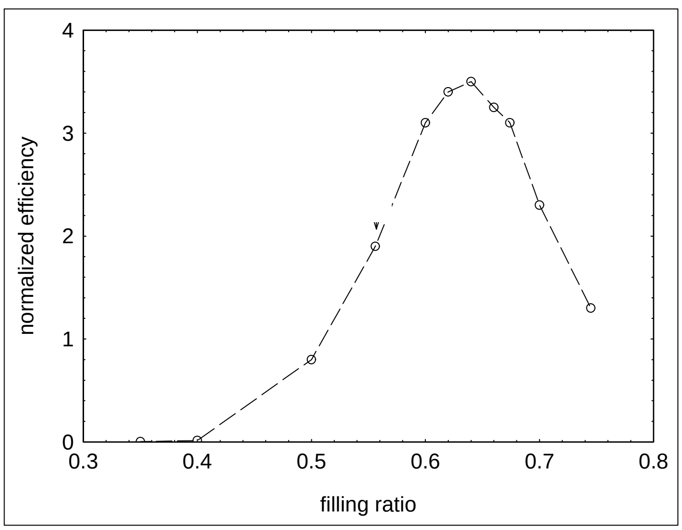

Figure 3: Normalized conversion efficiency versus the filling ratio of AlGaAs in the unit cell. The fundamental field is tuned to the first band edge resonance, the second harmonic field is tuned at the first resonance after the second order band gap.

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We numerically verified that the normalized efficiency grows exponentially as the number of periods to the power of 6 as predicted by our theories when phase matching is achieved. In conclusion the non phase matched interaction can provide a further enhancement to the efficiency/size ratio compared to the phase matched case if field's overlap inside the multilayer structure is considered and a proper distribution of the nonlinear material is chosen. Two devices have been designed for second harmonic generation in the visible range and in the near IR.

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2] G. D'Aguanno et al. J. Opt. Soc. Am. B 19, 2111 (2002)
3] M. Centini et al. Phys. Rev. E 60, 4891 (1999)

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